THEORETICAL STUDY OF POLLUTANT MIXING IN ROOMS INDUCED BY OCCUPANCY

L. Mora [1], A. J. Gadgil [2]

[1] LEPTAB, University of La Rochelle, Av. M. CREPEAU, 17042 La Rochelle, France
Phone: (+33) 5 46 45 83 10 Fax: (+33) 5 46 45 82 41 Email: lmora@univ-lr.fr
www: http://www-leptab.univ-lr.fr

[2] Indoor Environment Program, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
Phone: (+1) 510 486 651 Fax: (+1) 510 486 6658 Email: ajgadgil@lbl.gov
www: http://eetd.lbl.gov/IED/

Abstract
Airflow and pollutant transport models are commonly based on the approximation that air is instantaneously well mixed in a zone. In many circumstances this approximation is unsatisfactory. We present a semi-empirical model to predict the time required by a pollutant to disperse in a room, owing to the effects of room occupancy (room mixing induced by thermal plumes, stirring by people walking about and breathing). We base our estimates on previous experimental work correlating the mixing time for a pollutant pulse released in a room to the mechanical energy supplied to the room air. Our results suggest that people moving about in a room can induce rapid mixing. For example, the mixing time resulting from a person walking at 1.4 $m.s^{-1}$ in a 30 m^3 room is predicted to be about 4 minutes. In this case, the assumption that air is well mixed could be reasonable.

1. Introduction

Studies of pollutant dynamics in building commonly use the approximation that the air within a building zone is instantaneously mixed (Shair and Heitner, 1974; Nazaroff and Cass, 1986; Walton, 1997; Feustel, 1999). However sometimes, especially when pollutant sources are localized, toxicity is acute, and/or in a room with weak air movements, this approximation is unsatisfactory.

Pollutant dispersion can be characterized by the 'mixing time' for a point pulse release of a pollutant. Two experimental studies to measure the mixing time in the same $31m^3$ room under natural and mixed convection conditions (Baughman et al., 1994; Drescher et al., 1995) showed that the mixing time can vary from 2 to 42 min depending on the airflow conditions.

Real rooms commonly have occupants, who are breathing, have thermal plumes, and can even be walking about. This can lead to mixing of room air. How significant is this effect? When can it be ignored?

We assess the mixing time resulting from room occupancy, based on the empirical results of Drescher et al. (1994). Then, as an illustration, results are applied to the room used in the experiments of Baughman et al. (1994) and Drescher et al. (1995).

2. Background

2.1 Mixing-time definition
The mixing time, as defined by Baughman et al. (1994), equals the interval from the instantaneous release of a point-source pollutant until the relative standard deviation of concentrations (measured at well distributed points throughout the room) diminishes to 10% or less. This definition can be applied generally, however it is most useful when the mixing time is much shorter than the characteristic removal time of pollutants from the space.

2.2 Mixing by natural convection
Baughman et al. (1994) experimentally measured the rate at which a point pulse pollutant disperses within an unoccupied, 31-m^3, low air-exchange room under natural convection flow conditions. The room was approximately cubical, and a neutrally buoyant tracer was released at a point 1 meter from the two nearest walls, and 0.7 m from the floor. Mixing time was experimentally measured, with replicate experiments, under three airflow conditions: a quiescent case with nearly isothermal surfaces; strong convection from a 500-watt electric heater; and convection from a hot spot created on the floor from incoming

solar radiation. Air samples collected at 41 locations in the room permitted measurement of pollutant dispersion.

Under quiescent conditions, the maximum temperature difference measured in the room was less than 0.4°C and the mixing times were 80 min and 100 min in two experiments. With a 500 Watt electric heater the mixings times were 15 min and 13 min. Finally, incoming sunlight (estimated at 600 Watt) produced mixing times of 7 min and 10 min.

2.3 Mixing by forced convection

Drescher et al. measured the mixing time for a point-pulse release of a tracer under forced flow generated with blowers. The air circulation through the blowers ranged from 0 to 2 room volumes per hour. All measurements were replicated. The tracer concentration was measured at 9 appropriate locations in the room with passive datalogging monitors.

To subtract the influence of natural convection from the experimentally measured mixing time, Drescher et al. assumed the following relation between the mixing time due to forced convection alone, $\tau_{mix.fc}$, that due to natural convection alone, $\tau_{mix.nc}$, and the experimentally measured mixing time $\tau_{mix.expt}$.

$$\frac{1}{\tau_{mix.\exp t}} = \frac{1}{\tau_{mix.nc}} + \frac{1}{\tau_{mix.fc}} \tag{1}$$

Such relationship has been employed with success in the study of mixing in agitated tanks, for the "circulation time" decomposition (Tatterson, 1991, p. 208).

For the range of flow conditions, the experimentally measured mixing time ranged from 2min (for 2 room air volumes circulated per hour) to 42min (in quiescent conditions), and the mixing time due to forced convection alone was ranged from 2.4min to 22.9min.

From the experimental results, Drescher et al. correlated the mixing time from forced convection to the mechanical power, P, added to the room air as follows.

$$\tau_{mix.fc} = c\rho^{1/3} V^{5/9} P^{-1/3} \text{ [hour]} \tag{2}$$

where c is a proportionality coefficient experimentally determined (c=17.6±0.6), ρ is the density of air, and V the room volume.

3. Approach

We assess the mechanical power added to the room air by the presence and activities of occupants, and use the correlation derived by Drescher et al. to estimate the associated mixing time. Occupants can induce mixing by:

- thermal plumes due to buoyancy that develop above standing occupant's body,
- jets from exhalation by the occupants, and
- air movements caused by the occupant moving about the room.

In this study, the human body is approximated with a cylinder of diameter 0.70 m and height 1.70 m.

3.1 Mixing by thermal plume generated by occupants

The thermal plume rising from a human body can significantly influence the room air flow (Homma and Yakiyama, 1988; Murakami et al., 2000). We assume the body is at a uniform temperature T_b different from the room air temperature T_a. The surface temperature of the body in steady-state conditions is determined by the radiative-convective energy balance of the body, estimated using ASHRAE Fundamentals models. Assuming the air temperature T_a equals the wall surface temperature T_w (T_a=T_w=20°C), one can estimate the surface temperature of the clothing to be 27.3°C for a person standing in a quiescent room.

In these conditions, the Grashof number associated to the cylinder at temperature T_b representing the human body is:

$$Gr = \frac{\beta \, \Delta T \, g \, H^3}{\nu^2} = 4.8 \times 10^9 \tag{3}$$

The warm cylinder surface heats the adjacent air, which rises by natural convection along the cylinder walls. The velocity and temperature profiles of air are approximated in this region using the standard integral method used in convective heat transfer textbooks as shown below Then, the mechanical power added to the room air by a person, can be estimated by the expression:

$$P_{plume} = \frac{1}{2} \rho \int_A u^3 dA \tag{4}$$

where u is the vertical velocity profile in the boundary layer at the top of the cylinder, and A the annulus surface crossed by the flow (see Fig. 1).

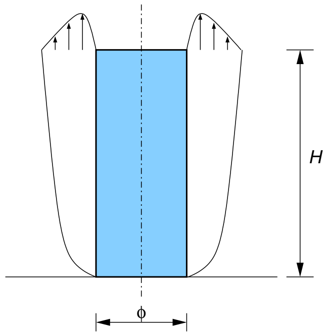

Fig. 1: *Boundary layer rising along the body model*

An approximate integral method is applied to a flat surface, assuming a cylindrical symmetry (see Fig. 2) to estimate the velocity profile at the top of the cylinder.

Integrated forms of momentum and energy conservation equations applied to a differential element of the boundary layer can be written:

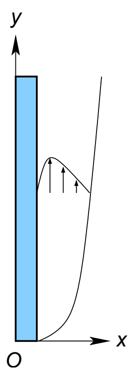

Fig. 2: *Boundary layer rising along a flat plate*

$$\frac{d}{dx}\int_0^\infty u^2 dy = \int_0^\infty g\beta(T-T_a)dy - \nu\left.\frac{\partial u}{\partial y}\right|_0 \qquad (5)$$

$$\frac{d}{dx}\int_0^\infty u(T-T_a)dy = -\alpha\left.\frac{\partial T}{\partial y}\right|_0$$

The boundary conditions of the problem are:

$$y=0: \quad \mathrm{u}=0, \mathrm{T}=\mathrm{T_b} \qquad (6)$$

$$y\to\infty: \quad \mathrm{u}=0, \mathrm{T}=\mathrm{T_a}$$

We assume that momentum and thermal boundary layers have the same thickness, $\delta = \Delta$, and assume the following forms for the velocity and temperature profiles:

$$\frac{u}{U}=\frac{y}{\delta}\left(1-\frac{y}{\delta}\right)^2, \quad \frac{T-T_a}{T_b-T_a}=\left(1-\frac{y}{\delta}\right)^2 \qquad (7)$$

where U is a scaling velocity, which is a function of x only and to be determined. We assume also power law variations for U and δ:

$$\delta = D.x^m, \quad U = X.x^n \qquad (8)$$

Integrating and solving the momentum and energy conservation equations using the preceding profiles yields the following solution for the velocity profile (Mills, 1992):

$$u_H(y)=\frac{80\alpha}{D^2}H^{1/2}\frac{y}{\delta(H)}\left(1-\frac{y}{\delta(H)}\right)^2 \qquad (9)$$

So the mechanical power can be now assessed by:

$$P_{plume}=\frac{1}{2}\rho\int_0^\delta u_H^3(y)\pi\left(y+\frac{\phi}{2}\right)dy \qquad (10)$$

The evaluation of the integral yields to:

$$P_{plume}=\frac{\pi}{2}\rho(80\alpha)^3\left(\frac{673\phi}{1680}\frac{H^{5/4}}{D^3}-\frac{921}{6930}\frac{H^{5/2}}{D^2}\right) \qquad (11)$$

with $D = 4\cdot 23.10^{-2}(T_b-T_a)^{-1/4}$ (12)

The numerical application leads to:

$P_{plume} \approx 1\times10^{-4}$ W

Using equation (2), the mixing time due to convection from a standing body in a 31m^3 room is:

$$\tau_{mix.plume}=c\rho^{1/3}V^{5/9}P_{plume}^{-1/3}\approx 45\,\mathrm{min} \qquad (13)$$

The mixing time associated to 5 persons standing in this room in the same conditions would be 26.7min.

3.2 Mixing by occupant exhalation

We assume the occupants breathe 6 l.min^{-1} with 10 breaths per minute (Bjorn and Nielsen, 1998). Assuming a sinusoidal variation of the mass flow rate and a nostrils open area of 0.0002 m^2, the maximum instantaneous air velocity near the nose is about 1 m.s^{-1}. Using equation 4, and based on the root mean square of air velocity, one can assess the mean of mechanical power added to air by the exhaling. In this case, P_{exhal}=4.3E-5 W, that leads to a mixing time $\tau_{mix.exhal}$ of about an hour.

3.3 Mixing by movement of occupants

We now consider people walking about at a uniform speed within the room, and the mixing caused by the resulting mechanical stirring. When a person is walking, drag effects generate air movement and turbulence that cause mixing. For a person walking at constant speed v, the drag force transmitted by the body to the air is estimated as:

$$F_D = C_d H\phi\frac{1}{2}\rho\frac{v^2}{g} \qquad (14)$$

For an aspect ratio (H/ϕ) of about 5, and for airflow conditions with a Reynolds number greater than 1000, Bloomer (2000) gives C_d=0.8.

So, the mechanical power supplied to the room air can be estimated by:

$$P_{movt} = F_D.v = C_d H \phi \frac{1}{2} \rho \frac{v^3}{g} \quad (15)$$

using this in equation (2) yields:

$$\tau_{mix.movt} = c \left(\frac{2g}{C_d H \phi} \right)^{1/3} \frac{V^{5/9}}{v} \quad (16)$$

Realistic indoor walking speeds ranges from 0.2m.s^{-1} to 3m.s^{-1}. For these two extreme values, associated mixing times for a 31 m^3 room are 27.1 min and 1.8 min, respectively. For an intermediate value of 1.4 m.s^{-1}, the mixing time is 3.9 min. Consequently, the mixing time has a very strong dependence on the actual walking speed of the occupants. On the other hand, dividing the mixing time by 2 requires 8 persons walking at the same speed in the room.

5. Discussion and Conclusion

We present estimates of the mixing time for a point-pulse pollutant release in a room, due to the presence of occupants. Our results suggest that the physical movement of the occupants can be a major contributor to the mixing in the room. Natural convection plumes from people standing in a room appear to be important for mixing only when air movements from all other causes are negligible. Contribution from jets from occupant exhalation is shown to be negligible. Experiments investigating mixing induced by heated manikins would be useful to further investigate mixing dynamics. The influence of the ventilation strategy (displacement vs fully mixed ventilation) on mixing dynamics should also be investigated, since equation (1) is intended only for the fully mixed ventilation strategy.

Simple semi-empirical models, such as the one developed here to estimate occupant impact on pollutant mixing, are useful for first order analysis. They provide faster ways to handle three-dimensional pollutant dispersion problems in occupied rooms, compared with computationally intensive methods such as Computational Fluid Dynamics.

Acknowledgments

This research was supported by the office of Non-proliferation and National Security, Chemical and Biological Non-proliferation Program of the U.S. Department of Energy under contract No. DE-AC03-76SF00098.
We would like to thank particularly Elisa Derby for improving the clarity of this document with her comments.

References

Baughman, A.V., Gadgil, A.J., and Nazaroff, W.W, Mixing of a Point Source Pollutant by Natural Convection Flow within a Room, *Indoor Air*, 4, 114-122, 1994.

Bjorn, E., Nielsen, P.V., CFD Simulation of Contaminant Transport between Two Breathing Persons. *In Proceedings of Roomvent'98*, 133-140, 1998.

Bloomer, J.J., *Practical Fluid Mechanics for Engineering Applications*, Marcel Dekker, New York, p. 275, 2000.

Drescher, A.C., Lobascio, C., Gadgil, A.J., and Nazaroff, W.W., Mixing of a Point Source Indoor Pollutant by Forced Convection, *Indoor Air*, 5, 204-214, 1995.

Feustel, H.E., COMIS – an International Multizone Air-Flow and Contaminant Transport Model. *Energy and Buildings*, 30, 3-18, 1999.

Homma, H., Yakiyama, M., Examination of Free Convection Around Occupant's Body caused by its Metabolic Heat*, ASHRAE Transaction*, 94(1), 104-124, 1988.

Mills, A.F., *Heat Transfer*, Richard D. Irwin Inc., Boston, 413-418, 1992.

Murakami, S., Kato, S., and Zeng, J., Combined Simulation of Airflow, Radiation, and Moisture Transport for Heat Release from a Human Body, *Building and Environment*, 35, 489-500, 2000.

Nazaroff, W.W., and Cass, G.R., Mathematical Modeling of Chemically Reactive Pollutants in Indoor Air, *Environmental Science and Technology*, 20, 924-934, 1986.

Shair, F.H., and Heitner, K.L., Theoretical Model for Relating Indoor Pollutant Concentrations to those Outside, *Environmental Science and Technology*, 8, 444-451, 1974.

Tatterson, GB, *Fluid Mixing and Gas Dispersion in Agitated Tanks*, McGraw-Hill, New York, 1991.